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Impact of automation: Measurement of performance, workload and behaviour in a complex control environment

Nora Balfe [a,*], Sarah Sharples [b], John R. Wilson [b,c]

[a] Centre for Innovative Human Systems, Trinity College Dublin, Ireland
[b] Human Factors Research Group, School of Mechanical, Materials and Manufacturing Engineering, University of Nottingham, Nottingham, UK
[c] Ergonomics Team, Network Rail, London, UK

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This paper is dedicated to Professor John Wilson who died in July 2013.

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A B S T R A C T

This paper describes an experiment that was undertaken to compare three levels of automation in rail signalling; a high level in which an automated agent set routes for trains using timetable information, a medium level in which trains were routed along pre-defined paths, and a low level where the operator (signaller) was responsible for the movement of all trains. These levels are described in terms of a Rail Automation Model based on previous automation theory (Parasuraman et al., 2000). Performance, subjective workload, and signaller activity were measured for each level of automation running under both normal operating conditions and abnormal, or disrupted, conditions. The results indicate that perceived workload, during both normal and disrupted phases of the experiment, decreased as the level of automation increased and performance was most consistent (i.e. showed the least variation between participants) with the highest level of automation. The results give a strong case in favour of automation, particularly in terms of demonstrating the potential for automation to reduce workload, but also suggest much benefit can achieved from a mid-level of automation potentially at a lower cost and complexity.

Impact statement

Research in the area of automation, and in particular in the examination of human interaction with different levels of automation, has normally been undertaken in laboratory settings using simple tasks and naïve participants where the level of automation can be easily manipulated. This research was undertaken with expert participants using complex simulation of three ecologically valid levels of automation and provides empirical field validation of some of the results found in laboratory studies.

1. Introduction

Automation, defined as the performance of tasks by machines (often computers) rather than human operators (Parasuraman and Riley, 1997), continues to be deployed in various industrial settings in order to increase efficiency and reduce variability. Cited benefits include the reduction of operator workload and error coupled with a reduction in labour costs (Dekker, 2004; Hollnagel, 2001). These benefits make automation very attractive to businesses wishing to increase efficiency while reducing costs. Numerous lab-based studies in the field of human factors have been undertaken to investigate the effects of automation and these have often found the benefits to be less clear-cut than might be expected (Parasuraman and Riley, 1997). For example, situation awareness may be reduced under high levels of automation (Kaber and Endsley, 2004) and workload may be increased under abnormal circumstances (Kantowitz, 1994). The level of reliability of automation is crucial, with a level below 70% believed to be worse than no automation (Wickens and Dixon, 2007). Among other weaknesses, such as the potential for programming errors (Wickens, 1992; Wiener and Curry, 1980), automation can lack the flexibility of human operators in the face of novel situations and thus difficulties can be encountered when the designers attempt to replace human problem solving abilities with automation. Hence, automation has thus far been most successful in closed loop systems, such as manufacturing systems, but humans are likely to remain vital to system performance in open loop systems, such as are commonly found in control environments, for many years (Parasuraman and Wickens, 2008).

* Corresponding author.
E-mail addresses: balfen@tcd.ie, norabalfe@gmail.com (N. Balfe).

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1.1. Rail signalling

Rail signalling is an example of an open loop system that cannot easily be fully automated. At its most basic, rail signalling involves authorising trains to move through the rail infrastructure while ensuring separation between all trains in an area. Separation in the rail context is defined in terms of sections of track (block sections) and under normal signalling rules only one train may occupy a section at any one time. As networks become more congested signalling systems face greater challenges in terms of performance. Decisions must be made on the ordering of trains through junctions and bottlenecks, and on the most effective management of failure situations. These challenges are particularly prevalent in the British rail network due to the complexity of the infrastructure and the congestion on key routes.

Nevertheless, automation has been present in British rail signalling systems for decades. At a basic level, the interlocking systems that ensure signallers do not set conflicting routes (i.e. prevent a second train being authorised to enter a block section) for trains can be regarded as an early form of automated decision support. Mechanical forms of interlocking have been in place since the 1800s and modern computer based interlockings still perform the same function today. Early signalling systems were controlled through sets of levers directly connected to the trackside equipment. Pulling these levers changed signal aspects or the position of points, allowing signallers to change the routes of trains and give train drivers the authority to proceed. These lever frame systems were the predominant form of signalling in the UK until the 1950s when eNtry-eXit (NX) panels were introduced. NX panels reduced the physical labour involved with signalling; the signaller simply presses buttons on the panel and the physical movement of the trackside equipment is achieved automatically. In the 1980s visual display unit (VDU) based signalling was introduced in Britain facilitating the development of more advanced decision making automation in the form of Automatic Route Setting (ARS). All three forms of signalling are still in use on the British rail network but only the modern VDU form is considered here.

1.2. Rail Automation Model

Models of levels of automation have typically been used to structure investigations into the impact of different levels of automation on key cognitive ergonomics concepts such as situation awareness (SA; e.g. Durso and Sethumadhavan, 2008; Endsley and Kiris, 1995; Kaber et al., 2000; Kaber et al., 2006) and workload (e.g. Kaber and Endsley, 2004; Kaber et al., 2006; Kantowitz, 1994). The levels of automation identified in the models can be used to distinguish levels of independent variables in experimental designs; if sufficient levels are defined, the effect of automation can being to be described on a continuum. The levels of automation incorporated in this study are described in terms of the model for types and levels of automation described by Parasuraman et al. (2000). The benefit of this model over those used by other researchers (e.g. Billings, 1991; Endsley and Kiris, 1995) is the ability to discriminate levels and types of automation between four functional dimensions of Information Acquisition, Information Analysis, Decision and Action Selection, and Action Implementation. Simply describing automation systems along one continuum does not give an appreciation of the different types of automation which may be present within systems and does not allow the analysis of the impact of automation at different stages of decision making.

Parasuraman et al. (2000) provide an interpretation of how automation will vary in each of these functional dimensions. For information acquisition, a low level of automation is suggested which simply helps gather the information; a mid-level is when the automation organises the information in some form, perhaps forming priorities; and a high level is where the automation filters the information so that a full set of raw data is not provided to the operator. Lower levels of information analysis automation may involve the use of algorithms to extrapolate incoming data over time or predict, and a higher level may involve integration of input variables into a single value. Automation may assist the operator with decision and action selection, for example by using conditional logic. Parasuraman et al. (2000) proposed that the decision selection automation level increases as the automation narrows the decision alternatives. Automation of the final stage, action implementation, may be the easiest type of automation to understand or observe with the level being defined by how much physical activity is replaced by automation.

The work of Parasuraman et al. (2000) was extended during this study to generate levels appropriate to the rail signalling domain in each of the four functional dimensions. A limitation of the existing scales used to describe the level of automation in each functional dimension developed by Parasuraman et al. is that they combine the functional dimensions, creating one scale for information acquisition and analysis and a second for decision-making and action implementation. This approach compromises some of the power of the four functional dimensions as the level of automation could differ independently in each. None of the other existing definitions of levels (e.g. Endsley and Kiris, 1995; Endsley and Kaber, 1999; Sheridan and Verplank, 1978) exactly matched the differences seen in the rail setting. Therefore four distinct scales

Table 1
Levels of automation in the Rail Automation Model.

Information acquisition	
None	Human gathers all information manually
Low	Information is gathered with assistance from ICT
Medium	Information gathering is shared between computer and human
High	Computer and technology provide most required information
Full	All information collected automatically
Information analysis	
None	Human analyses all information
Low	Basic analysis to identify immediate control requirements
Medium	Identification of control requirements and basic prediction of future states
High	Identification of control requirements and advanced prediction of future states
Full	Full predictive analysis performed using all required data
Decision and action selection	
None	Human makes all decisions
Low	Computer provides decision support to help ensure decisions are safe
Medium	Computer uses basic rules to make decisions between competing demands
High	Computer makes complex decisions between competing demands under normal circumstances
Full	Computer makes complex decisions under all conditions
Action implementation	
None	Human augments all actions
Low	Computer augments humans' physical labour
Medium	Computer implements any actions not requiring a decision
High	Computer implements most required actions
Full	Computer implements all control actions